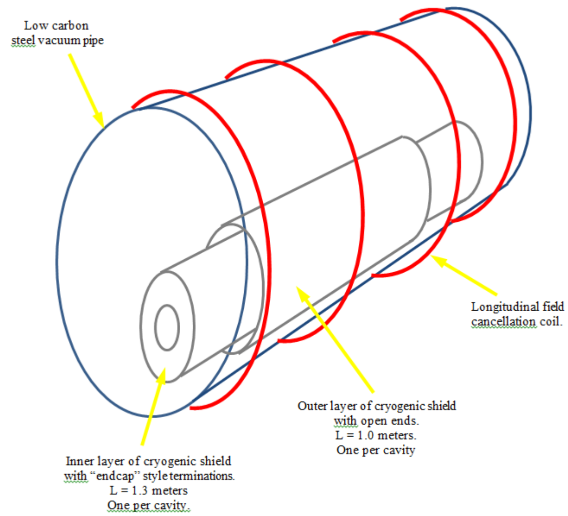
Some Options for Improving the Effectiveness of Magnetic Shielding in the LCLS-II Cryomodule.

I. Terechkine

As a result of the requirement of having an average quality factor of higher than 10^{10} for the cavities installed in the LCLS-II cryomodules, the average magnetic field at the location of the cavities before cooling down must not exceed 5 mG. Although challenging, this requirement can be met, but certain modifications of the existing design become inevitable. In the existing version of the cryomodule design, 1-mm thick magnetic shield made of the Cryoperm-10 material can do this work, but with little (or no) safety margin. In his brief note of Oct. 22, 2014, A. Crowford has summarized results of 2D modeling of the shielding system that uses a secondary shield, also made of Cryoperm-10 and located concentrically with the primary shield. With the one meter long shield, a safety factor of 1.8 could be obtained, which seems satisfactory. Fig. 1 shows schematically this arrangement.



Although the obtained result is encouraging, the 2D modeling cannot take into the account such details as the absence of the axial symmetry, which is clear in Fig. 1, and the presence of the vertical component of the magnet field.

In this note a 3D modeling of the system is attempted.

Consistent with the data obtained in the future tunnel of the accelerator, the following assumption is made about the external magnetic field: the component of the magnetic field directed parallel to the beam line B_X = 200 mG and the vertical component of the magnetic field B_Z = 500 mG; the magnetic field in the horizontal plain and perpendicular to the axis of the accelerator B_Y = 0. This assumption translates onto the 21.8º angle of the magnetic field vector relative to the vertical line.

Another significant assumption is the choice of material for the vacuum vessel of the cryomodule, which is magnetically soft steel. This choice was made mainly to reduce the cost of the cryomodule; the impact on the magnetic design is the loss of the shielding efficiency, as the permeability of steel can be quite low at low field level. In this study a conservative permeability value of 300 was used.

As it was agreed earlier, no reasonable shielding scheme could be found without the use of a compensating winding that zeroes the longitudinal field inside the cryomodule. This longitudinal component was found to interact unfavorably with the geometry of the vessel and of the primary magnetic shield; both systems have fairly high aspect ratios.

Fig. 2 shows longitudinal magnetic field map for the inner part of the cryovessel (coordinates in the figure are in meters) with the compensation field adjusted to cancel the longitudinal component. Graphs show distribution of the longitudinal and the vertical magnetic field (in mG) along the axis. At this point, no internal (primary) shielding is introduced yet.

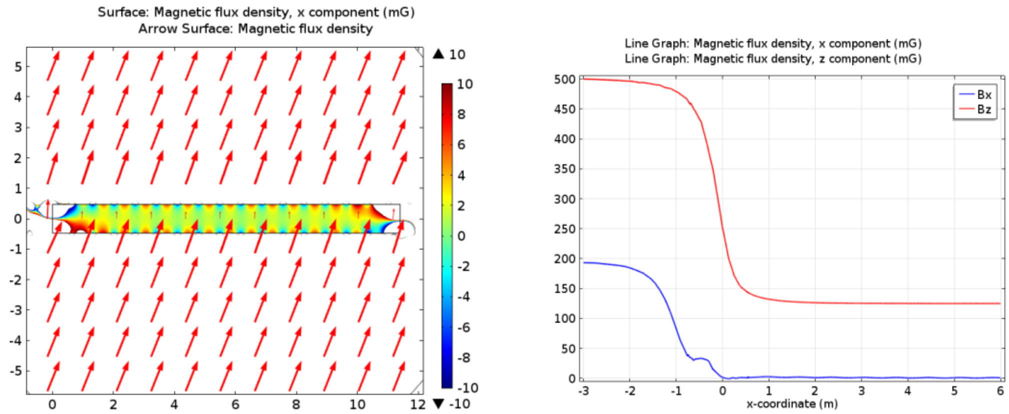


Fig. 2: Magnetic field inside cryovessel; magnetic vessel (μ = 300) and compensation coils are used.

Compensating coils allow effectively dump the longitudinal component of the external field, but this cannot be said about the vertical component which remains quite significant. If higher permeability of the vessel material can be assumed, the situation with the vertical component of the field can be significantly improved.

The primary shields (μ = 9000) effectively reduce magnetic field in the area where the cavities are installed. Fig. 3 shows plots of the longitudinal and vertical magnetic field (in mG) along the axis of the cavity.

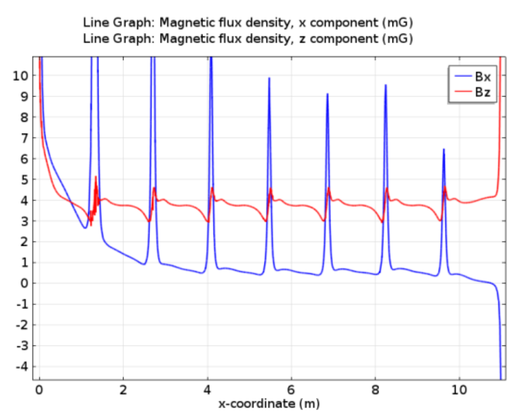


Fig. 3. Magnetic field distribution along the beam line.

The longitudinal field in the first two devices is significantly higher than for the rest of the cavities; this happens because the location of the first cavity is close to the end of the vacuum vessel, as it is shown in Fig. 4, where position of the first two cavities is shown relative to that of the vacuum vessel. Also shown in this figure (in color: magenta and cyan) positions of two versions of the secondary shield, which will be discussed later in this note.

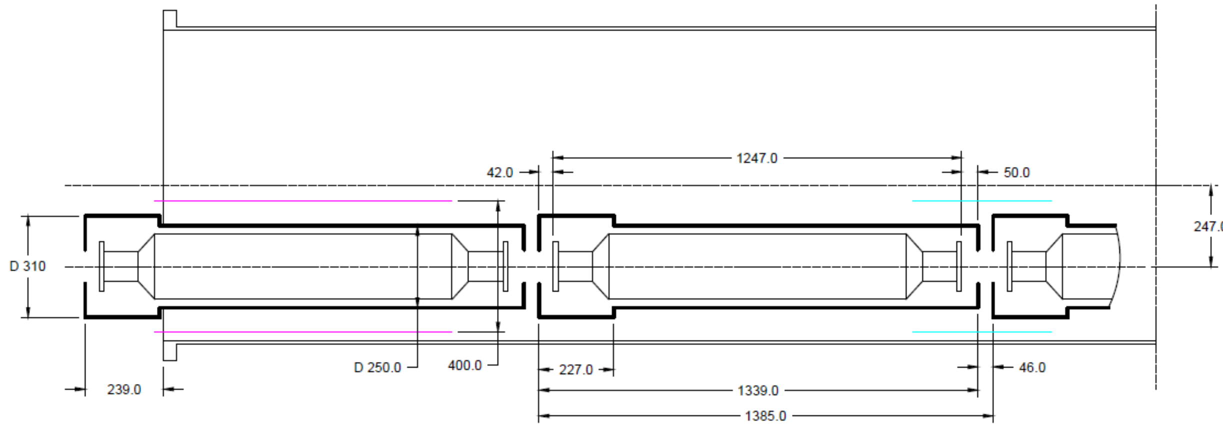


Fig. 4: Position of the cavities relative to the vacuum vessel.

To improve the situation with the "vessel end" effect, an auxiliary magnetic shield must be used outside the bellow that connects two neighboring cryovessels. **The compensating coils must also be placed with regular intervals along the total length of the accelerator**. This configuration will be assumed further in the study.

Before the secondary shield is introduced, it has sense to investigate how the thickness of the primary shield affects the shielding efficiency. Figures 5, 6, and 7 show the profile of the magnetic field (B_X and B_Z components) along the length of three cells, starting with the first one. Zero of the X coordinate in the graphs coincides with the left end of the vacuum vessel. The thickness of the shields increases from 1 mm in Fig. 5 to 1.5 mm in Fig. 6 to 2 mm in Fig. 7.

The curves are built along three lines: the first one (blue) coincides with the beam line (axis of the cavity), the second one is 90 mm above the axis, and the third one is 90 mm below.
We see that both components of the field scale almost linearly with the thickness. Average field in the volume occupied by the cavity also scales linearly:
B_{av} = 4 mG for t = 1.0 mm;
B_{av} = 3 mG for t = 1.5 mm;
B_{av} = 2 mG for t = 2.0 mm;

So, **the goal of the study, which is finding a way to provide sufficient safety margin for the fringe field, could be achieved just by increasing the thickness of the primary shield to 1.5 mm**, which is a standard thickness for Cryoperm-10 sheets as well as Amunil-4K material.

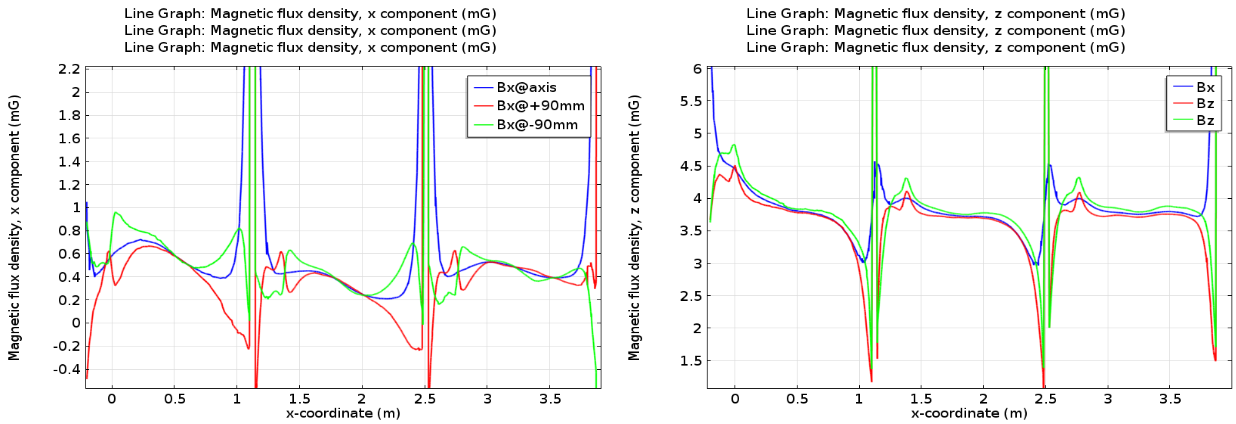


Fig. 5. Magnetic field profile along the bean line; t = 1.0 mm

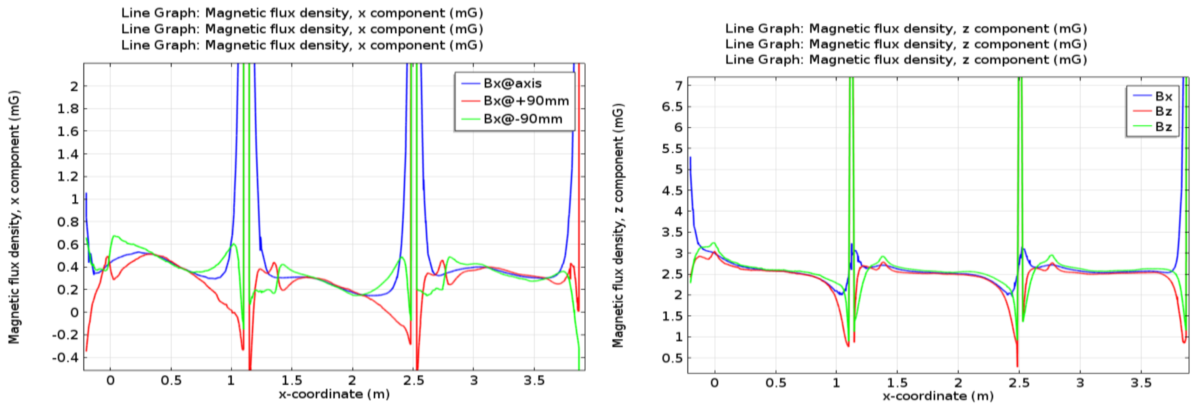


Fig. 6. Magnetic field profile along the bean line; t = 1.5 mm

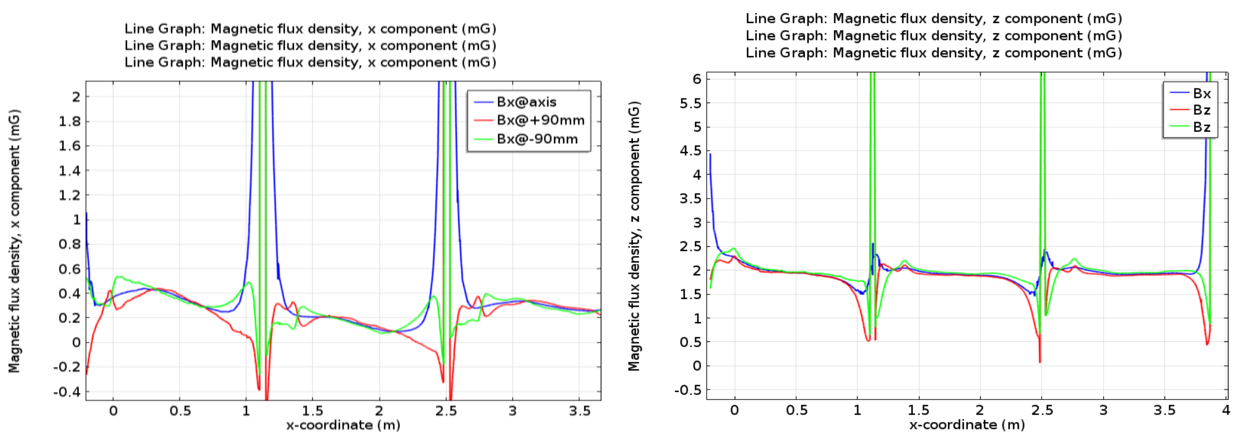


Fig. 7. Magnetic field profile along the bean line; t = 2.0 mm

As the next step of this study, impact of the secondary shield configuration on the efficiency of shielding was investigated. Two cases were studied:

- the secondary shield is placed concentrically with the primary shield and centered to the gap between adjacent primary shields.

- the secondary shield is placed concentrically with the primary shield and centered to the cavity;

Schematically these two cases are shown in Fig. 4: cyan contour for the first case (Gap Shield in Fig. 8) and magenta for the second (Body Shield in Fig. 8). For both cases, the radius of the shield of 200 mm was chosen. The length of the shield was changed and the magnetic field calculated for each configuration. Results are summarized in Fig. 8, which shows the averaged magnetic field in the volume occupied by the first cavity as function of the length of the shield. One millimeter thickness of the shield was assumed in all the cases.

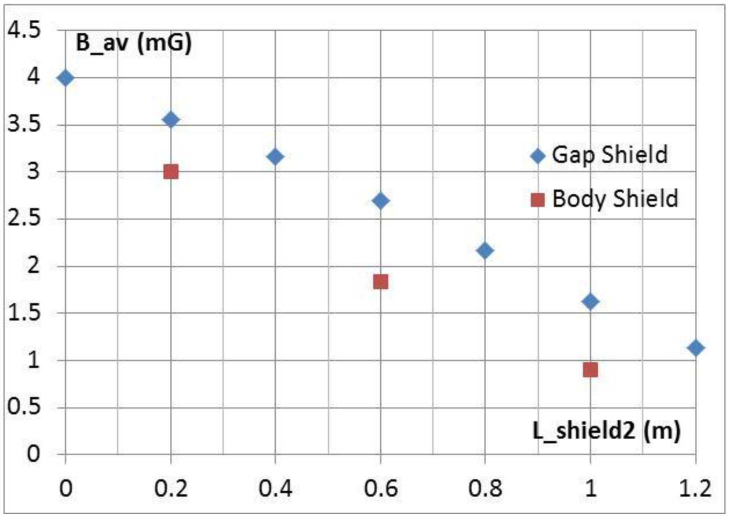
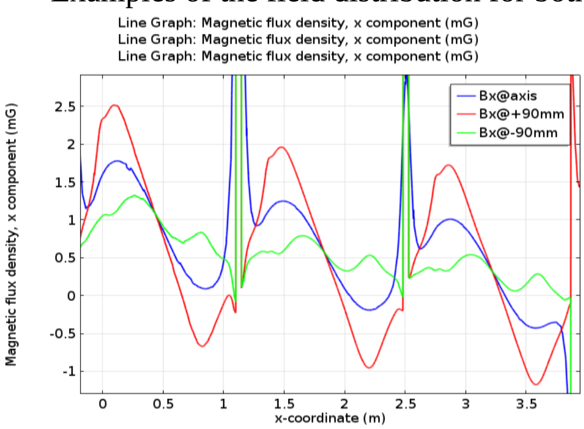


Fig. 8: Average magnetic field as function of the length of the shield; t = 1 mm.

For the **Gap Shield** case, the length of the shield has little impact on the maximum value of the longitudinal component of the field. The maximum value of the vertical component has clear correlation with the shield length though. This field component has its maximum in the center of the cavity.

For the **Body Shield** case, both components change significantly with the length of the shield. The transverse field has its maximum near the ends of the primary shield.

Examples of the field distribution for both cases are shown in figures 9 and 10 for L = 0.6 m.



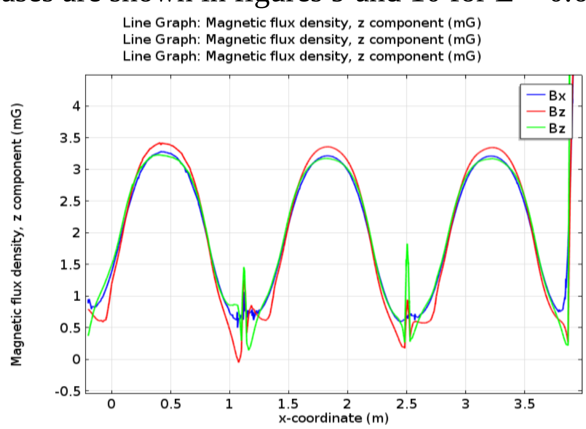


Fig. 9: Magnetic field distribution along the axis of the system for the 0.6 m long Gap Shield.

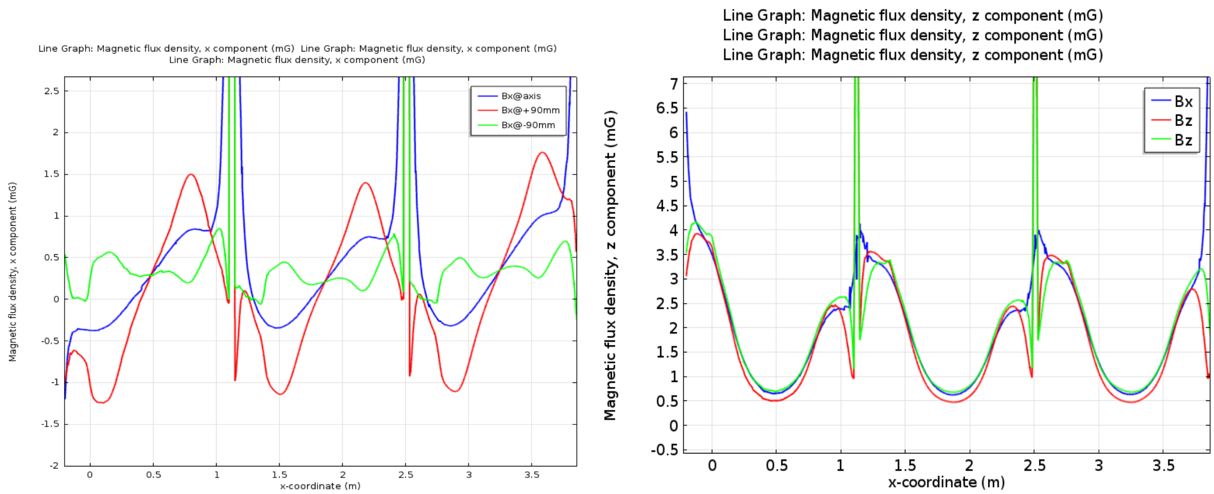


Fig. 10. Magnetic field distribution along the axis of the system for the 0.6 m long Body Shield.

In the case of the Body Shield, the impact of the thickness is minimal (for short systems) for both the longitudinal and the transverse field.

In the case of the Gap Shield, increasing thickness of the material has direct and almost proportional impact on the shielding efficiency. So, the negative impact of shorter length can be compensated by increasing the thickness. Only transverse field changes with this transformation; impact for the longitudinal field is minimal.

That the shielding efficiency is roughly proportional to the amount of the material in the shield points to another possibility worth to consider - using several short secondary shield assemblies instead of one long. This can simplify the way the shield accommodates LHe piping in the cryomodule. Fig. 11 shows configuration where 200 mm long, 1 mm thick cylinders are used that are placed both to cover the gaps and the middle part of the cavity. Corresponding magnetic field traces are in Fig. 12.

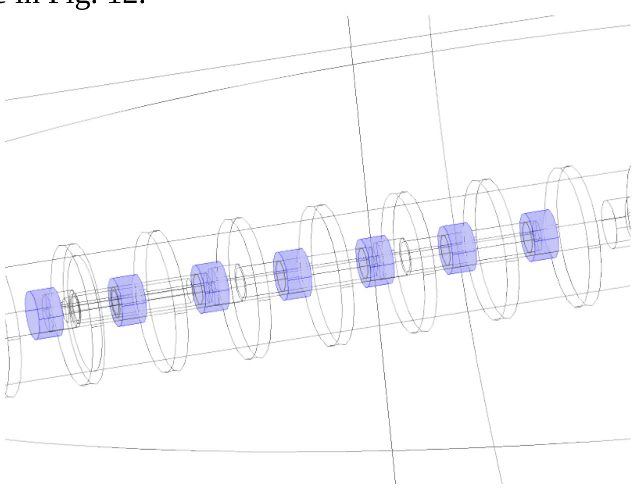
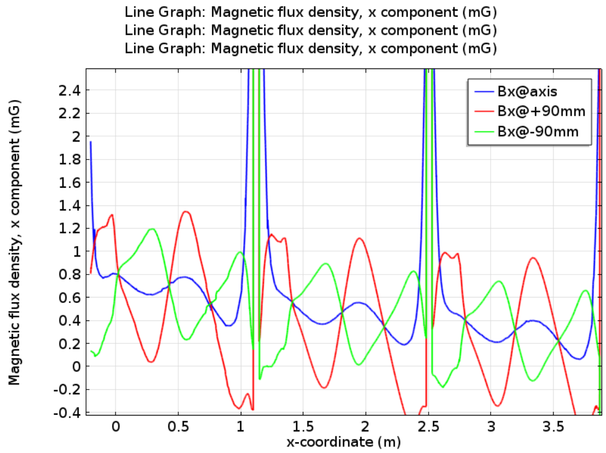


Fig. 11. Alternative “short period” configuration if the magnetic shield; L = 200 mm.



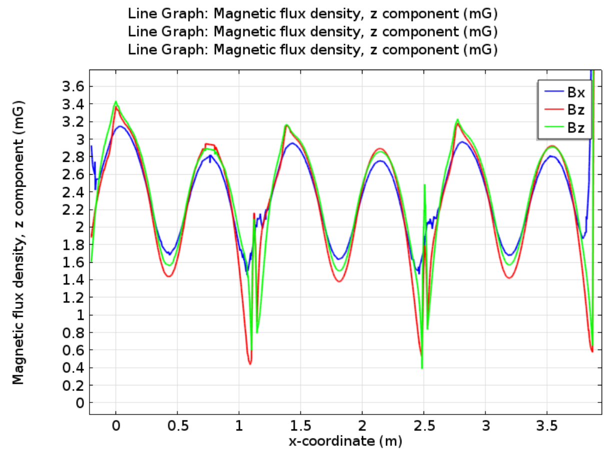


Fig. 12. Magnetic field along the “short period” system; L_shield = 200 mm

The average field in the volume of the first cavity in the case is 2.6 mG; in Fig. 8 this value falls between the values of the average field of the two main cases.

In the case of this combined shielding scheme, the length of the secondary shield can be further reduced. In the case of the 100 mm length, the magnetic field averaged through the volume of the first cavity is 3.1 mG, which is just ~20% higher than for the 200 mm length. Increasing the thickness of the secondary shield to 2 mm does not provide any sizable improvement, but increasing the number of the shield pieces per the length of the cavity does help. Using 1 mm shield system where three 100 mm long pieces are used for every cavity, brings the average field back to the 2.6 mG level. Again, the thickness of the shield has little impact on the shielding efficiency here. Corresponding geometry is shown in Fig. 13, and traces of magnetic field along the lines Z = -90 mm, 0, and +90 mm are in Fig. 14.

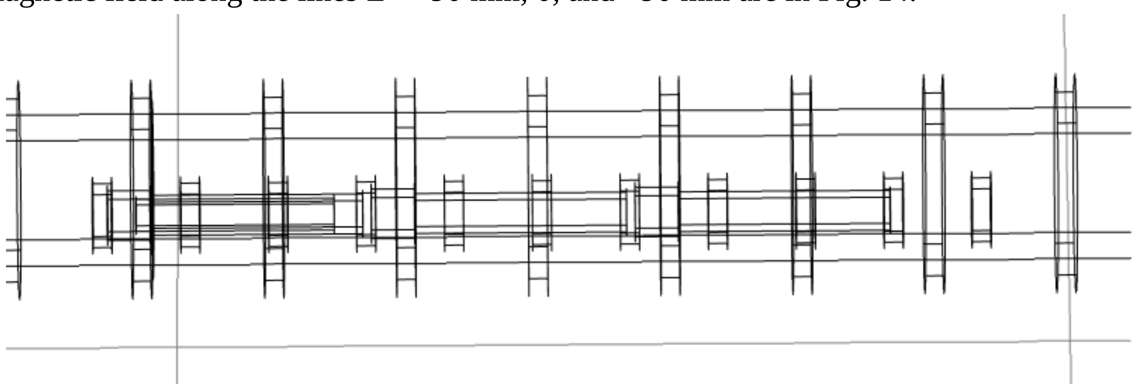


Fig. 13. Location of 100 mm long secondary shield pieces in the case when three pieces are used for every cavity in the cryomodule.

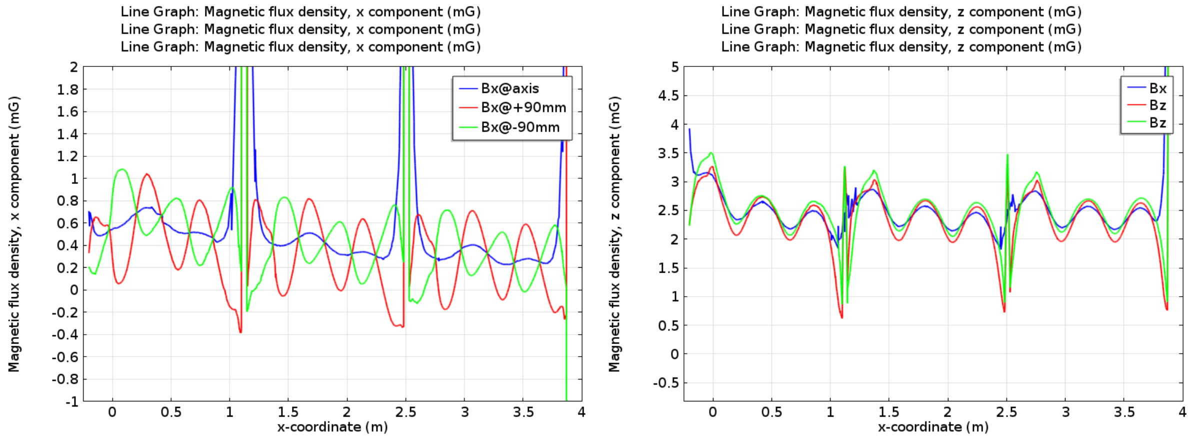


Fig. 14: Magnetic field along the system with three 100 mm shield pieces for every cavity in the cryomodule; t_shield = 1.0 mm.

<u>Conclusion</u>:

1. It seems feasible getting the level of magnetic field inside cryomodules of LCLS linacs below 3 mG provided the compensation coils are used and the global magnetic shield is modified by increasing the effective length.
2. There are several ways of reaching the shielding efficiency goal including increasing the thickness of the primary shield and using secondary shield system.
3. The secondary shield system, if chosen, can be configured in several ways. Reasonable approach to the shielding system design in the environment of the cryomodule can be based on the mechanical design optimization with iterative computational support to validate shielding properties.